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14. ABSTRACT

Ejecta fragments from cratering on Tethys' coorbital (Trojan) moons result in impacts onto Tethys that are unusual in terms of size distribution, impact velocity, and location [1]. We find that crater ejecta escaping from L4 (Telesto) or L5 (Calypso) can explain two major features of Tethys' geologic record: the lens-shaped albedo feature on the far side [e.g. 2], and the overall surplus of 1-20 km diameter impact craters [2-5]. Further analysis of these connections can help tie together our understanding of Saturnian system dynamical evolution and chronometry.

15. SUBJECT TERMS

NASA, USAF, planetary science, Saturn, Tethys, Telesto, Calypso, impact physics, dynamical evolution, surface chronometry

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CO-ORBITAL DEBRIS AS A SOURCE OF SMALL IMPACTORS AND ALBEDO FEATURES ON TETHYS.
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Summary: Ejecta fragments from cratering on Tethys' coorbital (Trojan) moons result in impacts onto Tethys that are unusual in terms of size distribution, impact velocity, and location [1]. We find that crater ejecta escaping from L4 (Telesto) or L5 (Calypso) can explain two major features of Tethys' geologic record: the lens-shaped albedo feature on the far side [e.g. 2], and the overall surplus of 1-20 km diameter impact craters [2-5]. Further analysis of these connections can help tie together our understanding of Saturnian system dynamical evolution and chronometry.

Background: The diversity of Saturn's mid-sized icy moons (MIMs) has proved challenging for primordial accretion formation models, due mainly to the occurence of past resonances that would have captured the moons [e.g. 5]. Hence, several new formation models have been proposed, such as reaccretion of the MIMs after catastrophic collisions [5,6] or the formation of rocky "seeds" within the ring system that accrete ice during subsequent outward migration [7]. Each of the proposed formation mechanisms implies different ages for the MIMs; current estimates range from roughly 4 billion years to only 100 million years.

The geologic records of the MIMs can provide a critical constraint on their ages. However, much is unknown about cratering on these moons. The source population(s) and size frequency distribution of primary impactors is not well-known, nor is the distribution of secondary and sesquinary craters that form from impacts into icy surfaces. On Tethys, debris from its coorbital moons, Calypso and Telesto, may also have contributed to its crater population [1].

When compared with the other icy satellites of Saturn, Tethys has many more small craters, with diameters of 1 to 10 km, relative to large craters [2,3]. In addition, younger regions of Tethys have more small craters (4 to 20 km) than older regions, suggesting a more recent, planetocentric population [4]. Tethys also has several albedo features of uncertain origin, including a lens-shaped feature along the equator of the leading hemisphere [2,8,9].

In [1], we modeled the evolution of ejecta escaping from the five largest craters on Calypso and the seven largest craters on Telesto. We determined that a large fraction of ejecta created by primary impacts onto either coorbital moon is likely to impact Tethys. We now place these results into context within Tethys' global geologic record by considering the relationships between ejecta deposition and geologic features and by estimating the likely sizes of impact craters formed on Tethys by incoming coorbital ejecta. We find it very likely that coorbital debris contributes to the surplus of small craters on Tethys and the albedo lens, although the mechanism of the latter is uncertain.

Methodology: Using the Z-model to track ejecta from impacts onto the coorbital moons, Calypso and Telesto, showed that most ejecta impacts Tethys [1]. A large portion of this ejecta impacts at relatively high velocities (>5 km/s) and predominantly low (oblique) impact angles; these impacts are heavily clustered along the equator in the leading hemisphere of Tethys and correspond to the albedo "lens" identified in both *Voyager* and *Cassini* data (see Fig. 1).

The Z-model cannot provide an estimate of ejecta size, which is critical to determining whether (and which) craters on Tethys were formed by ejecta fragments from the coorbitals. Instead, we apply the scaling laws for ejecta fragment sizes derived secondary craters on icy satellites [10], which depend on the ejection velocity of the fragments, the size of the transient crater, and the gravity of the moon.

The craters on the coorbital moons, that we modeled in [1], are between 1.35 and 3.8 km in diameter. To impact Tethys, the ejected fragments must have ejection velocities large enough to escape the Hill sphere of the moon [11-13], which are 4.7 m/s and 5.6 m/s for Calypso and Telesto, respectively. Scaling the values (Fig. 14 of [10]) results in mean fragment diameters of 1.2 km and 2.2 km for ejecta from 3-km primary craters on Calypso and Telesto, respectively. These are the largest fragments that reach the Hill escape velocity. Higher velocity fragments will have smaller diameters – e.g. the highest scaled velocities from [10] result in mean fragments diameters of ~670 m.

We use the impactor size to crater diameter relation from [13] (their Eq. 13), which was derived for Saturnian icy satellites, to determine the likely crater diameters that would form as a result of 1-2 km fragments impacting Tethys. The crater diameter depends on the impact velocity. The Z-model results suggest a variety of impact velocities [1], so we use 350 m/s as a lower bound and 10 km/s as an upper bound. With these values, we find that craters from 4 to 15 km in diameter could form on Tethys from coorbital debris of the estimated mean fragment size. For the higher ejection velocity fragments, with diameters <1 km, the resulting impacts on Tethys would still be between 2 and 10 km, depending on the impact velocity.

An alternative approach is to determine the smallest fragment that would create a resolvable crater on Tethys, given the current imaging data available. We can confidently identify craters larger than 1 km in diameter at the best *Cassini* image resolution of ~215 m/pix. Using the same impactor size to crater diameter relation [13], we find that a 10 km/s fragment greater than 41 m in diameter would create a crater on Tethys of at least 1 km, whereas a 350 m/s fragment would need to be at least 194 m in diameter. These values are 2 to 10% of the mean fragment diameters we calculated above, which supports the idea that craters formed by coorbital debris are present in the observable cratering record on Tethys. High-resolution *Cassini* images of the surface of Tethys are suggestive of such impacts in the form of grooves, scours, and elongated craters (see our companion abstract, Ferguson et al., 2017).

Tethys has a surplus of small (<10 km diameter) craters relative to large craters, when compared to its neighboring moons, and an excess of 4-20 km craters on its younger terrains [2-4]. Craters formed by coorbital ejecta fall within this size range and could be the source of excess small craters on Tethys. However, our results rely on a scaling law derived from large basins on relatively large icy moons [10]. Hence, more sophisticated modeling of the impact process is required to confirm the ejecta fragment sizes we have estimated here, and ultimately determine the extent to which coorbital impact debris has generated 1 to 20 km craters on Tethys. If Calypso and Telesto are among the last remaining fragments of initially larger coorbital moons, then some larger craters on Tethys may also have formed by impacting coorbital debris.

Conclusions: Impacts of coorbital ejecta onto Tethys should be a frequent, global process [1]. We find that ejecta fragments would be large enough to contribute to the population of 1-20 km impact craters on Tethys. Due to the oblique angle of many impactors, these impacts may also be the source of scours, grooves, and elongated craters that are observed in many regions of Tethys (see companion abstract, Ferguson et al., 2017). Also, relatively high-velocity, oblique impactors are heavily clustered at the location of the albedo lens feature observed on Tethys. More sophisticated modeling of the impact process on Calypso and Telesto and analysis of the geomorphology of Tethys' surface will further constrain the extent to which Trojan debris has modified Tethys.

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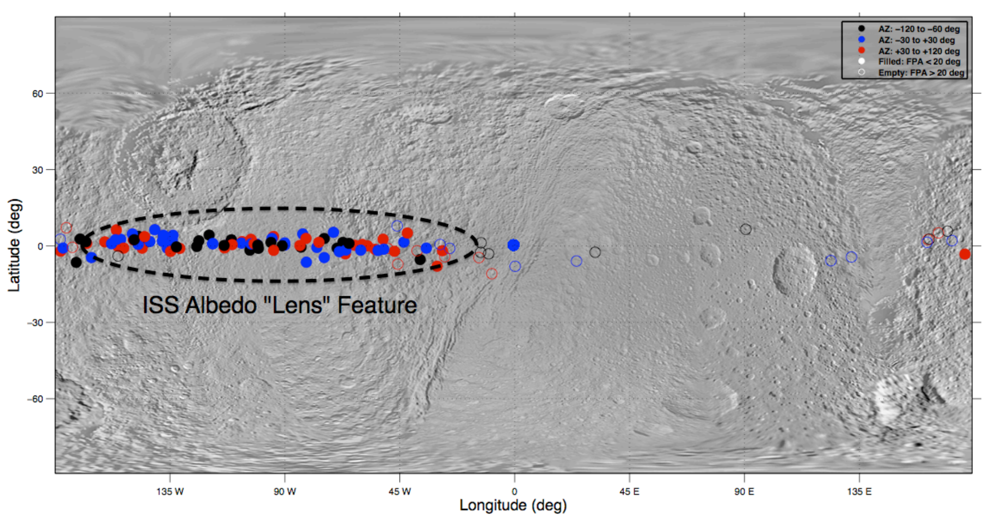

Figure 1: Higher-velocity (>5 km/s) ejecta from impacts onto the coorbital moons (colored circles) would impact Tethys in a narrow region that coincides with the location of an albedo feature (dashed line) identified by *Cassini* ISS. The above impact map shows ejecta from Calypso; results are similarly concentrated for Telesto ejecta. Colors correspond to different ejection angles. Filled circles are low-angle impacts (<20°); empty circles represent higher angle impacts. Lower velocity impacts, at any angle, are more evenly distributed across the surface (not shown).